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New physics at e+e− colliders

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Abstract : Possibilities of observing new physics, i.e., of observing new particles, or unexplored properties of known particles, at future electron-positron colliders are reviewed. Some general properties of linear colliders are reviewed first. The main topics covered under new physics are measurements of anomalous gauge-boson couplings and of various properties of the top quark

Keywords : Electron-positron collisions, linear colliders, electroweak gauge bosons, top quark

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1. Introduction

In this talk, I will review the possibilities of observing "new physics", *i.e.* of observing new particles, or unexplored properties of known particles, at future e^+e^- colliders. I will dwell on signatures of new physics, rather than discuss origins of new physics in any detail. Moreover, due to the limited time available, I will mainly concentrate on gauge boson and top quark properties.

The e^+e^- colliders presently operational at high energies (at or above the Z mass) are SLC (Stanford Linear Collider) at SLAC, Stanford, USA, and LEP (Large Electron Positron Collider) at CERN, Geneva, Switzerland, with LEP being in the higher energy (LEP2) phase (161 GeV and above) in recent times, planned to reach 190 GeV. The next generation of e^+e^- colliders, which would be of the linear type in the centre-of-mass (cm) energy range of 300 GeV and above, have been discussed with regard to their feasibility, characteristics, design and physics capabilities for quite some time now [1–3]. Possible locations considered are at SLAC (Next Linear Collider, or NLC) DESY (TESLA and the S-Band Linear Collider, or SBLC), KEK (Japan Linear Collider, or JLC), CERN (CERN Linear Collider, or CLIC) and Budker Institute, Protvino/Novosibirsk (VLEPP)[1]. Also considered

[1] In this talk, the term NLC will refer to any one of these, and not necessarily the one proposed for SLAC.

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are options like e^-e^-, γe and $\gamma\gamma$ colliders. The photon beams of high energy and intensity are proposed to be obtained by back-scattering of high energy electrons by low-energy photons obtained from an intense laser beam [4].

The advantage of e^+e^- colliders over hadronic colliders is mainly in the cleaner environment. By using leptonic initial states, electroweak interactions are more conveniently studied because there would be no spectator jets which arise in the case of hadronic colliders. A fewer number of kinematic cuts to suppress backgrounds are needed because of the cleaner environment, and thus the effective luminosity is better than at hadronic colliders. Moreover, theoretical uncertainties due to partonic distribution functions are also avoided.

Despite the spectacular success of the standard model (SM), there are still some outstanding questions, which future experiments can help to answer. One of the questions is regarding the mechanism of electroweak symmetry breaking. If it is the orthodox Higgs mechanism, the Higgs particle must be found. In that case experiments can determine its mass, its CP properties, and its couplings. In particular, the couplings should be proportional to the mass of the particles the Higgs couples to. If the symmetry is broken by some dynamical mechanism without explicit scalars, signatures of this mechanism should be revealed by experiments. For example, new resonances are predicted in technicolour models. In any case, the top mass being close to the Fermi scale, electroweak properties of the top quark may give important clues to the symmetry breaking mechanism.

A related issue is the strength and nature of gauge-boson interactions. If there is no Higgs with mass below about 1 TeV, gauge-boson interactions would become strong, with new non-perturbative effects. Even if the interactions are weak, nonstandard effects like the presence of heavy particles or compositeness could alter the nature and magnitudes of the triple and quartic couplings of gauge bosons from those predicted by SM. Presently these are measured at the $p\bar{p}$ collider at Tevatron with large errors. It will be the task of future colliders to improve upon this accuracy.

Extensions of SM which have been widely considered are grand unification, supersymmetry and technicolour. All these predict new particles, which under certain circumstances may be in the accessible range of e^+e^- accelerators in the range of 500 GeV – 2 TeV.

2. The Physics possibilities

We summarize below a possible physics programme for a future linear e^+e^- collider. While it will not be possible in this talk to go into the details of all the topics included in this summary, the topics of new top-quark physics and electroweak gauge boson couplings will be dealt with at greater length later on.

(i) Top properties :

The cross section for $e^+e^- \to t\bar{t}$ increases rapidly just above threshold, and a threshold scan can be used to measure the top quark mass up to an accuracy of $\Delta m_t < 500$ MeV. The couplings of the gauge bosons (γ, Z, g) to $t\bar{t}$, including anomalous magnetic and electric dipole couplings (together with their weak and colour counterparts) could be measured with good accuracy in $e^+e^- \to t\bar{t}(g)$. Similarly, the Yukawa coupling $t\bar{t}H$ can be measured directly in $e^+e^- \to t\bar{t}H$. In the decays of t and $\bar{t}$ produced in e^+e^- collisions, the chirality of the $\bar{t}b$ charged current can be tested.

(ii) Test of QCD :

The running of the strong QCD coupling $\alpha_s\ (q^2)$ can be measured at higher energies and compared with theoretical extrapolations from lower energies. The nature and magnitude of the gluon couplings to $t\bar{t}$ and to other gluons can be investigated.

(iii) Electroweak gauge bosons :

Triple and quartic couplings of the electroweak gauge bosons can be studied with great accuracy in a number of production processes, principally, $e^+e^- \to W^+W^-$. Masses and couplings of a new gauge boson Z' occurring in extensions of SM can be studied in $e^+e^- \to f\bar{f}$ (f stands for a fermion), with $f\bar{f}$ arising from a real Z', if light, or from a virtual γ, Z, Z' [5].

(iv) Higgs boson :

Higgs particles with masses upto 200 GeV would be accessible for $\sqrt{s} \approx 500$ GeV through the reaction $e^+e^- \to ZH$, $e^+e^- \to \nu\bar{\nu}H$, *etc.* Once discovered, the mass, CP properties and couplings of the Higgs can be determined [6].

(v) Supersymmetry :

Supersymmetry, needed to stabilize the light scalar mass in the presence of a hierarchy of scales as in grand unified theories, predicts a rich spectrum of new particles. The extended Higgs sector and the supersymmetric partners can be studied for a wide range of masses and other parameters.

(vi) Additional fermions :

Charged and neutral fermions predicted in extensions of SM could be produced in pairs, or in association with ordinary fermions. A range of masses between $\sqrt{s}/2$ and $\sqrt{s}$ can be probed, depending on the production mechanism.

3. Characteristics of the colliders

To avoid prohibitive losses of energy due to synchroton radiation the circular colliding-ring design has to be discarded for e^+e^- colliders beyond LEP2. The high energy colliders will have to be linear colliders.

It is expected that the linear e^+e^- colliders will be realized in two phases. The first phase will cover the cm energy range from LEP2 energy to 500 GeV. In the second phase, the energy will be moved up to 1 to 2 TeV. The luminosity at $\sqrt{s}$ = 500 GeV would be of the order of 10^{33} cm^{-2} sec^{-1}.

Cross sections would be of the order of $\sigma(e^+e^- \to \mu^+\mu^-) \approx 500\, fb$ at $\sqrt{s}$ = 500 GeV. At a luminosity of $\mathcal{L} = 10^{33}$ cm^{-2} sec^{-1}, for a running time of 10^7 sec (1/3 of a year), the integrated luminosity would be $\int \mathcal{L} dt = 10\, fb^{-1}$, which is equivalent to 5000 $\mu^+\mu^-$ pairs. For higher energies, the luminosity must be scaled up as the square of the energy to keep up the same production rates.

A high luminosity is achieved by squeezing e^+ and e^- into bunches of extremely small dimensions. As a result, large electromagnetic fields arise, which acting on an individual e^- or e^+ as it traverses a colliding bunch, bends its trajectory. Thus large amonut of radiation is emitted during the crossing of bunches, and the effect is known as "beamstrahlung". This not only results in loss of cm energy, it also implies that the initial sharp spectrum is smeared. Moreover, radiated photons produce spurious events, some of which could also be hadronic. Thus the cleanness of the e^+e^- collider could easily be destroyed [7].

In narrow-band beam designs, the effects can be reduced to the level of 1%. Also, the hadronic events produced by photons are of the same order as those induced by ordinary bremstrahlung. The beamstrahlung photons would also produce background e^+e^- pairs, concentrated in cones of half-angle of about 10° around the beam pipe.

Longitudinal polarization of e^- is possible at linear colliders. For example, SLC uses strained Ga-As cathodes to polarize electrons, which are then accelerated without loss of polarization. A high degree of polarization can be achieved, exemplified by ~80% polarization at SLC. Polarization of e^+ is not so easy; proposals for it do exist, however This is in contrast to circular colliders, where transverse polarization is more natural, and longitudinal polarization is difficult to achieve. The longitudinal polarization of the electron beams would be useful in discriminating between different types of couplings of quarks and gauge bosons, as well as in improving the sensitivity of experiments to certain anomalous couplings.

4. Anomalous gauge boson couplings

Although the standard electroweak model has been verified in recent years at LEP and SLC to a high degree of preceision, non-Abelian self-couplings of weak vector gauge bosons have not been tested directly with significant precision. Tevatron results from two-gauge-boson production have not yet reached a precision better than order unity. Ongoing measurements at LEP2, future measurements at an upgraded Tevatron and at LHC will improve upon this precision considerably, but cannot match the expected precision of a 500 GeV NLC, much less that of a 1 TeV or 1.5 TeV NLC.

There exist indirect constraints on anomalous couplings from precision measurements at the Z resonance, arising from gauge bosons in the loop. But the calculation of these diagrams suffers from ambiguities. The anomalous couplings could arise, for example, due to unexpected contribution of new particle propagators in loops.

4.1. Parametrization of triple gauge boson couplings :

An effective Lagrangian for the WWV ($V = Z, \gamma$) vertex is written as [8]

$$\begin{aligned}\mathcal{L}_{WWV}/g_{WWV} &= ig_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu}\\ &+ i\frac{\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right)\\ &+ g_5^V \varepsilon^{\mu\nu\rho\sigma}\left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right)V_\sigma + \tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu}\\ &+ i\frac{\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}. \end{aligned} \qquad (1)$$

Here $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $\tilde{V}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$. The normalization factors are $g_{WW\gamma} = -e$ and $g_{WWZ} = -g\cos\theta_W$. The couplings include 3 CP-violating ones : g_4^V, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$, and one CP even but C and P violating coupling g_5^V. In most studies only the 3 CP even as well as P even couplings are considered.

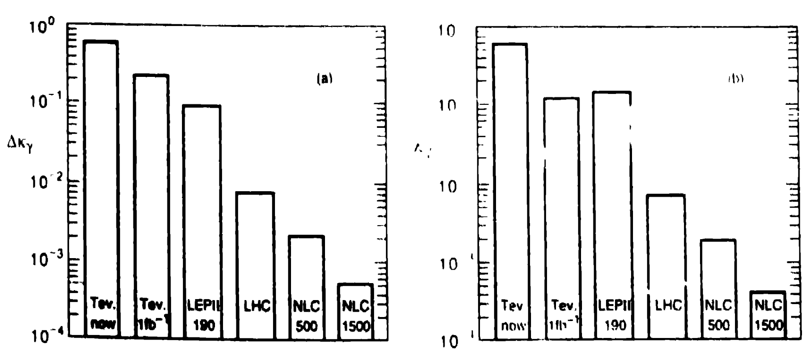

Figure 1. Comparison of limits on anomalous triple gauge-boson couplings at various colliders, from ref. [10]

In SM at tree level, $g_1^V = \kappa_V = 1$, $\lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = 0$. The couplings should actually be written as form factors with momentum dependent values. However, for a process like $e^+e^- \to W^+W^-$, where the W^+, W^- and the virtual photon and Z always have the same momenta, the form factors have fixed values. The couplings for $q^2 = 0$, where q is the momentum of the virtual photon, are related to static properties of the W as follows :

W electric charge : $\quad g_1^\gamma (q^2 = 0) = 1$

W magnetic dipole moment : $\quad \mu_W = \frac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma)$

W electric quadrupole moment : $\quad Q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$

A particular form of effective Lagrangian which is more restrictive than the most general one possible was considered by Hagiwara *et al* [9], which is known as the HISZ scenario, after the initials of the authors. This Lagrangian is the linear effective Lagrangian in which the coupling of gauge bosons is obtained by gauging an effective Lagrangian for new physics which is invariant under $SU(2)_L \times U(1) \times SU(3)_C$, with the further restriction of equal couplings for SU(2) and U(1) terms.

$e^+e^- \to W^+W^-$ at NLC can be used to test the HISZ hypothesis by determining the γ and Z couplings independently.

4.2 Present measurements :

At Tevatron, so far a few events have been observed for WW and WZ production and $\mathcal{O}(10)$ events for $W\gamma$ production. These are consistent with SM. These can be used to obtain limits

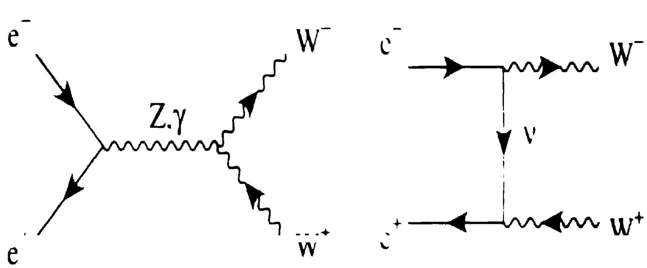

Figure 2. Feynmann diagrams for the process $e^+e^- \to W^+W^-$

on corrections to the gauge boson couplings. These limits are of the order of unity. For example, the D0 collaboration has obtained the 95% C.L. limits of $-1.8 < \Delta\kappa_\gamma < 1.9$ (assuming $\lambda_\gamma = 0$), and $-0.6 < \lambda_\gamma < 0.6$ (assuming $\Delta\kappa_\gamma = 0$) [10]. Here the parameter Λ used in the parametrization of the form factors is assumed to be 1 TeV. After the main injector upgrade, Tevatron will collect 1–10 fb^{-1}. With an integrated luminosity of 10 fb^{-1}, the limits will be competetive with those from LEP2. At LEP2, with $\int \mathcal{L}dt = 500\, pb^{-1}$, 95% C.L. limits of the order of 0.1 are expected on the anomalous couplings, considered one at a time. At the present time there are already some results from LEP2 available. However the limits are as yet poor.

When LHC goes into action, its higher cm energy will result in considerable improvement of accuracy. For example, with an integrated luminosity of $100\,fb^{-1}$, limits of the order of $5-10 \times 10^{-3}$ are expected to be obtained.

The limits that would be obtained from various colliders, including NLC, are shown in Figure 1, taken from [10].

4.3. *Measurement at NLC :*

4.3.1. $e^+e^- \to W^+W^-$:

The process $e^+e^- \to W^+W^-$ is the simplest process involving the triple vector couplings. The amplitude gets contribution from three diagrams shown in Figure 2. Of these the first two can get extra contributions from anomalous *WWV* couplings, whereas the third one gives the same contribution as in SM.

Due to the absence of spectator partons, *W* pair events can be reconstructed better at NLC than at hadron colliders. To a good approximation, full energy and momentum conservation can be applied to the visible final states.

An $e^+e^- \to W^+W^-$ event can be characterized by 5 angles : The production angle Θ of the W^- with respect to the electron beam, the polar and azimuthal angles θ^* and ϕ^* of one daughter of the W^- in the W^- decay frame, and corresponding decay angles $\bar{\theta}^*$ and $\bar{\phi}^*$ of one of the W^+ daughters. (In practice, initial-state photon radiation and final-state photon and gluon radiation complicate the picture, as does the finite width of the W).

At high energies, $e^+e^- \to W^+W^-$ is dominated by the t-channel ν_e exchange, leading primarily to very forward W's. This makes a majority of the events difficult to observe.

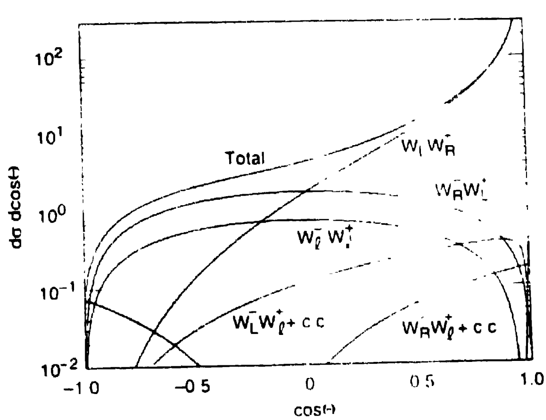

Figure 3. Angular distribution of W pairs with different polarization combinations in $e^+e^- \to W^+W^-$. L, R and l denote left-handed, right-handed, and longitudinal polarizations. The differential cross sections are given in units of R at $E_{cm} = 1$ TeV. This figure is taken from [3].

However, the amplitudes affected by anomalous couplings are not forward peaked. The central and backward W's are measurably altered in number and helicity by these couplings. *W* helicity analysis through the decay angular distributions can be used to probe them. Figure 3 shows the angular distributions of *W* pairs of various polarization combinations.

The most powerful channel is the one in which one *W* decays leptonically and the other hadronically. The branching ratio for this is about 30%. With this channel, full momemtum reconstruction is possible. Although the branching ratio for a totally hadronic channel is larger, discrimination power is lost because of the inability to tag fully the charge of the quarks. The purely leptonic channel has branching ratio of about 0.05, and suffers from kinematic ambiguities due to two undetected neutrinos.

Initial-state radiation and finite *W* width leads to some degradation, particularly when imposing cuts to suppress far-off-shell events and low effective cm energy events.

A comparison of the capabilities of LEP2 and NLC in measuring the anomalous gauge couplings $\Delta\kappa_\gamma$ and λ_γ in the HISZ scenario is shown in Figure 4. Figure 5 shows simultaneous limits on γ and Z couplings at NLC. These are taken from [11].

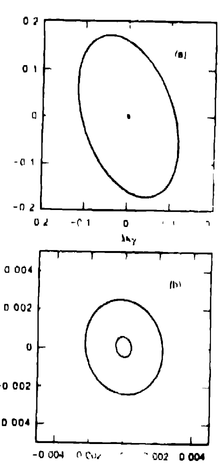

Figure 4. 95% C. L. *contour* in the HISZ scenario The outer contour in (a) is for $\sqrt{s}$ = 190 GeV and 0.5 fb^{-1}. The inner contour in (a) and the outer contour in (b) is for $\sqrt{s}$ = 500 GeV with 80 fb^{-1} The inner contour in (b) is for $\sqrt{s}$ = 1.5 TeV with 190 fb^{-1}

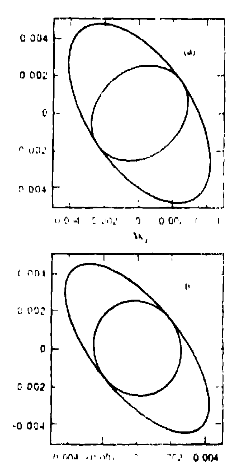

Figure 5. 95% C L *contours* for simultaneous fits at $\sqrt{s}$ = 500 GeV and 80 fb^{-1}

In general, precision at NLC is $\mathcal{O}$ (10^{-3}) for $\sqrt{s}$ = 500 GeV, and $\mathcal{O}$ (few × 10^{-4}) for $\sqrt{s}$ = 1.5 TeV. Electron beam polarization helps to disentangle couplings and check HISZ.

The possibility of studying CP violation in the process $e^+e^- \to W^+W^-$ has been studied by Chang *et al* [12], Mani *et al* [13] and Spanos and Stirling [14].

4.3.2. Other reactions at NLC :

Various other processes have been considered, which have different relative importances at different values of $\sqrt{s}$. Particularly important are the ones with one massive gauge boson production :

$$e^+e^- \to e^\pm \overset{(-)}{\nu} W^\mp, \tag{2}$$

$$e^+e^- \to e^+e^- Z, \tag{3}$$

$$e^+e^- \to \gamma Z, \tag{4}$$

$$e^+e^- \to \nu\bar{\nu}\gamma, \tag{5}$$

$$e^+e^- \to \nu\bar{\nu} Z. \tag{6}$$

The last process (6), together with decay of Z in to $q\bar{q}$ has recently been considered by Choudhury and Kalinowski [15]. They point out that this process can give bounds comparable to those expected from $e^+e^- \to W^+W^-$. This process has also been examined from the point of view of CP-violating couplings. It was shown in [16] that a forward-backward asymmetry of the Z, which if observed would signal CP violation, singles out the P-even, C-odd coupling g_4^Z.

5. Top quark physics

The top quark is so much heavier than the other quarks that much of the intuition of ordinary hadronic physics is simply invalid when applied to $t\bar{t}$ systems. The first major difference is that t decays to an on-shell W boson, and has a lifetime short compared to typical hadronic scales. The decay width is given approximately by the expression

$$\Gamma(t \to bW) = \frac{\alpha_w}{16}\frac{m_t^3}{M_W^2}\left(1 - \frac{M_W^2}{m_t^2}\right)^2\left(1 + \frac{2M_W^2}{m_t^2}\right)\left(1 - 2.9\frac{\alpha_s}{\pi}\right)$$

$$\approx (1.4\ \text{GeV})\left(\frac{m_t}{175\ \text{GeV}}\right)^3. \tag{7}$$

Thus the top decays before non-perturbative strong interaction precesses have time to act [17] : $\frac{1}{\Lambda_{QCD}} \approx 10^{-23}$ sec, whereas $\frac{1}{\Gamma} \approx 3.6 \times 10^{-24}$ sec.

This implies that the top quark is amenable to perturbation theory. Moreover, in production and decay processes, the top quark retains its spin orientation. The decay $t \to Wb$ can then be used as an analyzer of top polarization.

5.1 Gauge couplings of the top quark :

Test of non-standard couplings to electroweak gauge bosons can be addressed at e^+e^- colliders by exploiting the large forward-backward and polarization asymmetries in $t\bar{t}$

production and decay. These reflect very different couplings of the left- and right-handed components. For example if $E_{cm} \gg m_t, M_Z$,

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to t\bar{t}) = \frac{3\pi\alpha^2}{4s}\left[|f_{LL}|^2(1+\cos\theta)^2 + |f_{LR}|^2(1-\cos\theta)^2\right], \quad (8)$$

where
$$|f_{LH}|^2 = \left| -\frac{2}{3} - \frac{\left(\frac{1}{2} - \sin^2\theta_W\right)\left(I_H^3 - \frac{2}{3}\sin^2\theta_W\right)}{\sin^2\theta_W\cos^2\theta_W} \right|^2$$

$$= 1.4 \text{ for } e_L^- e_R^+ \to t_L \bar{t}_R$$

$$= 0.2 \text{ for } e_L^- e_R^+ \to t_R \bar{t}_L \quad (9)$$

with $H = L, R$, $I_L^3 = \frac{1}{2}$, $I_R^3 = 0$. A left-handed electron beam dominantly produces forward-moving, left-handed top quarks. In a more realistic case, the angular distribution of $t\bar{t}$ pairs in $e_L^- e^+ \to t\bar{t}$ for $\sqrt{s} = 500$ GeV is shown in Figure 6, taken from ref. [3].

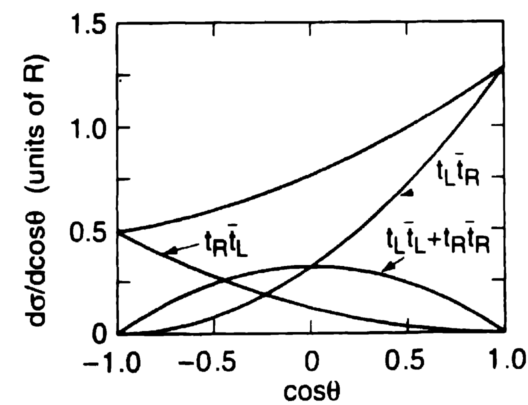

Figure 6. The angular distribution of $t\bar{t}$ pairs of various helicity combinations in $e_L^- e^+ \to t\bar{t}$ at cm energy 500 GeV, taken from [3].

Deviations from the predicted angular distributions can signal anomalous couplings parametrized by :

$$\mathcal{L} = g_{ttV}\left[F_{1L}\bar{t}\gamma^\mu t_L V_\mu + F_{2L}\frac{1}{2m_t}\bar{t}\sigma^{\mu\nu}t_L V_{\mu\nu} + (L \leftrightarrow R)\right], \quad (10)$$

$V = \gamma, Z$ and $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$. It may be noted that CP invariance implies $F_{2L} = F_{2R}$, and the difference between F_{2L} and F_{2R} is proportional to the CP-violating electric or weak dipole moment of the top quark. Experimentally, signals of CP violation would be CP-violating asymmetries or correlations amongst final state momenta.

Various anomalous quantities which can be investigated are magnetic and electroweak dipole moments, and wrong chirality component in the coupling to W.

5.2. *Anomalous magnetic moment :*

Since in SM there is only a small number of t_R produced in the backward direction, the backward direction is sensitive to small anomalous magnetic moment. The angular dependence can be used to bound the magnetic moment to a few percent [18].

5.3. *Electric and "weak" dipole moments :*

The measurement of these CP-violating dipole moments necessarily needs decay distributions. A measure of CP violation is $N(t_L\bar{t}_L) - N(t_R\bar{t}_R)$, the difference in the numbers of like helicity top and antitops. This number-asymmetry can be converted to asymmetries in the energies and momenta of decay products [19,20]. CP-odd correlations, with and without beam polarization can be used to measure or bound the dipole moments [21–25]. A simple asymmetry in the semileptonic decay products may be used to probe the imaginary parts of the dipole moments. This is simply the charge asymmetry in the number or leptons : $\left[\Delta\sigma(l^+) - \Delta\sigma(l^-)\right]/\Delta\sigma$ [26]. In this case an angular cut on the forward and backward directions is needed for a nonzero answer. Another simple asymmetry is the sum of forward-backward asymmetries of the l^+ and l^- in semileptonic events : $\left[\Delta\sigma_{F-B}(l^+) + \Delta\sigma_{F-B}(l^-)\right]/\Delta\sigma$ [26]. Limits on dipole moments of the order of a few times 10^{-18} e cm would be possible with the use of polarized electron beams.

5.4. *Chirality of the $\bar{t}b$ current :*

The lepton energy distribution in the semileptonic decay $t \quad bW^+ \to bl^+\nu_l$ depends sensitively on the chirality of the current :

$$\frac{d\Gamma}{dx_l} \quad \begin{array}{ll} x_l(1-x_l) & \text{for } V-A \\ (x_l-\mu^2)(1-x_l+\mu^2) & \text{for } V+A, \end{array} \tag{11}$$

where $\mu^2 < x_l = \dfrac{2E_l}{m_t} < 1$, with $\mu = M_W/m_t$. Deviation from V–A leads to the stiffening of the energy spectrum, with a nonzero value at the upper end of the energy distribution.

5.5. *Higgs-top Yukawa coupling :*

A direct way to obtain the $Ht\bar{t}$ Yukawa coupling is to look at the process $e^+e^- \to t\bar{t}H$, where Higgs is produced by bremsstrahlung off a t or $\bar{t}$ in $e^+e^- \to t\bar{t}$ [27]. SM predicts a reasonable number of events for Higgs mass of about 100 GeV or less.

For $M_H > 2m_t$, the process $e^+e^- \to Zt\bar{t}$ gets an extra contribution from $e^+e^- \to ZH$, $H \quad t\bar{t}$. This would produce an enhancement in the cross section around the Higgs mass [28]. However, this effect is large for lower top masses, and if the top mass is larger than 175 GeV, as it nows seems to be, the enhancement may not be easy to observe.

6. Concluding remarks

An attempt has been made to describe the important new physics that can be studied at a future high energy linear e^+e^- collider. While the topics of top quark properties and gauge boson interactions have been described in some detail, certain other important topics like supersymmetry, Higgs searches, extra gauge bosons and heavy fermions could not be taken up because of lack of time. Reviews of these can be found in [2] and references therein.

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[1] For a compact update of the operational features of linear colliders, see *Physics Monitor*, CERN Courier 37 April 1997 p 16

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